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STANDARDIZED FAULT-TOLERANT SENSING NODES FOR AN INTELLIGENT TURBINE ENGINE CONTROL SYSTEM (PREPRINT)

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Orbital Research, Inc./Linear Dimension, Inc.

Alireza R. Behbahani

Engine Systems Branch
Turbine Engine Division

MAY 2013

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14. ABSTRACT
Control systems can vary from small and simplex to large and complex, but in all cases the systems consist of a controller, at least one actuator (as simple as a solenoid) and enough sensors to determine the result of the actuation, or in other words, the state of the system. In many cases, the size of the system, meaning either the physical size of the components, or the distance separating the sensors from the controller, presents problems in wiring, noise immunity, and power distribution. By configuring the control system to use distributed smart nodes, these problems are mitigated to various degrees determined by the requirements of the system and the amount by which control can feasibly be distributed.

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STANDARDIZED FAULT-TOLERANT SENSING NODES FOR AN INTELLIGENT TURBINE ENGINE CONTROL SYSTEM

Mike Willett, and Alireza Behbahani
Orbital Research Inc. and Air Force Research Laboratory

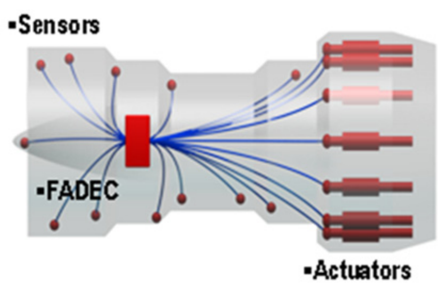
Key words: distributed engine control, high temperature electronics, digital networks, Fault-tolerant Sensing

Abstract: Control Systems can vary from small and simplex to large and complex, but in all cases the systems consist of a controller, at least one actuator (as simple as a solenoid) and enough sensors to determine the result of the actuation, or in other words, the state of the system. In many cases the size of the system, meaning either the physical size of the components, or the distance separating the sensors from the controller, presents problems in wiring, noise immunity, and power distribution. By configuring the control system to use distributed "smart" nodes, these problems are mitigated to various degrees determined by the requirements of the system and the amount by which control can feasibly be distributed.

I. System Architecture

Centralized Architecture. The following **Figure 1** shows a representation of a centralized control system on a turbine engine. All actuators and sensors are point-to-point cabled to the controller (FADEC) which houses electronics to interface to each node in the system. The electronics are cooled to remove the heat of the engine and heat generated by the electronics themselves.

Each function resides within the FADEC and uses Unique Point-to-Point Analog Connections to System Effectors and Sensors



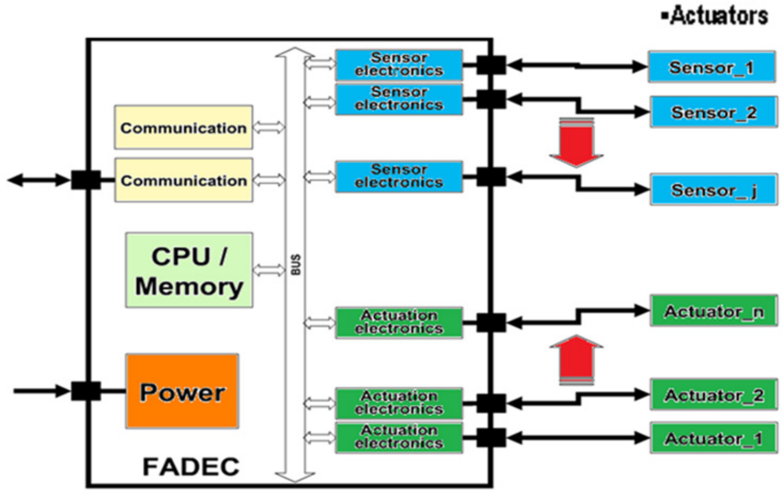


Figure 1: Centralized Control System

Distributed Architecture. In contrast,
Figure 2 shows a representation of a distributed control system on the same turbine engine. The actuators and sensors interface to Smart Nodes which, in turn communicate to the FADEC via a digital communication bus.

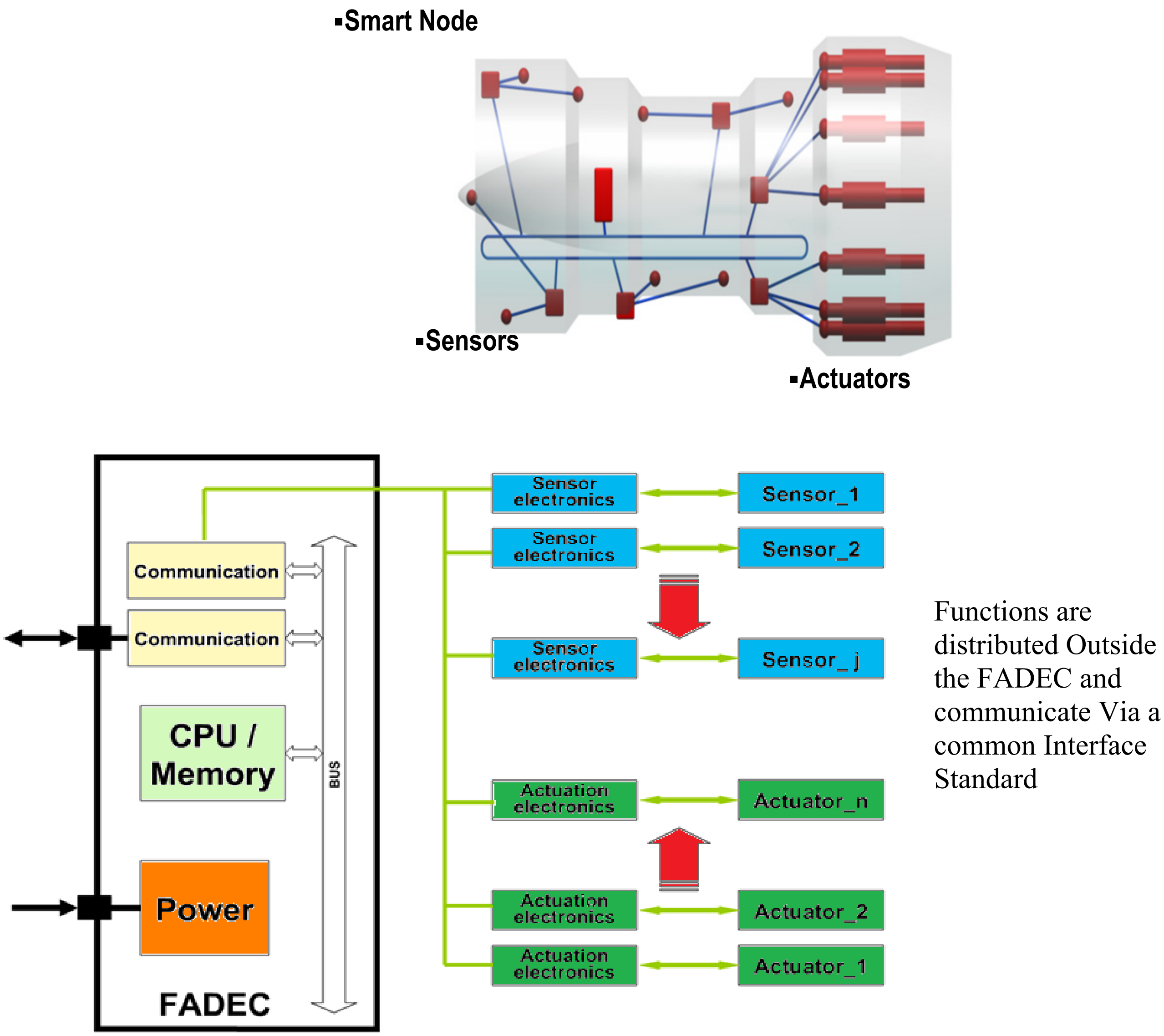
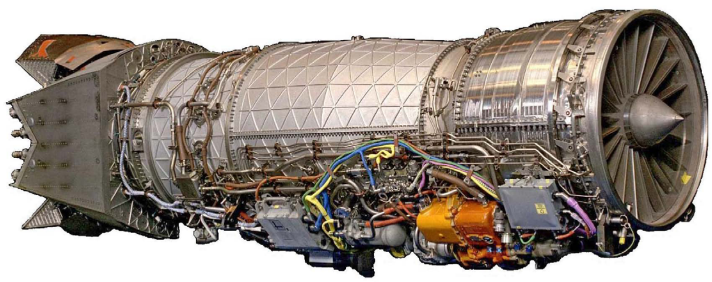


Figure 2: Distributed Control System

How is Distributed Control Different? Both of these system architectures may achieve the required robust control of the turbine engine. However, the distributed control scheme may provide some desired improvements:

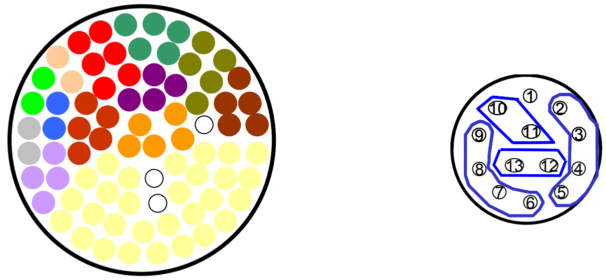
Analog signal lines are significantly shortened improving S/N ratio. **Figure 3** shows the large distances that some analog signal bundles must traverse to connect to an interface.



Engine Controls and Accessories Comprise a Substantial Portion of Total Engine Weight as Shown in This Core-Mounted Fuel-Cooled Military Control Implementation

•(Courtesy of Pratt & Whitney)

Figure 3: Turbine Engine Showing Controls



79 pin (20 Devices) 13 pin (Redundant Comm)

Figure 5: Cable Bundle from Typical FADEC and Replacement

Cabling is greatly reduced. **Figure 5** shows two typical examples of a cable bundle controlling 20 devices in the existing FADECs today (central). The one on the left contains 76 connections. The one on the right contains 13 connections of digital communication.

FADEC cooling is reduced (or eliminated). By removing interface circuitry from the FADEC, the power dissipation is reduced, and by connecting by digital data bus, the FADEC can be moved to a less hostile environment; it no longer needs to be as close as possible to the effectors it controls. **Figure 6** shows a temperature profile of a typical turbine engine. It can be seen that areas in the combustion and exhaust are too hot for even high temperature electronics. Liang-Yu Chen, Beheim, G, and others (see references at the end) have shown that high temperature wireless sensing and data transmission system including packaging technology, and SiC electronic devices can be deployed for those applications. In these cases, sensors and actuators will be controlled from smart nodes that are either cooled, or positioned farther away than normal.

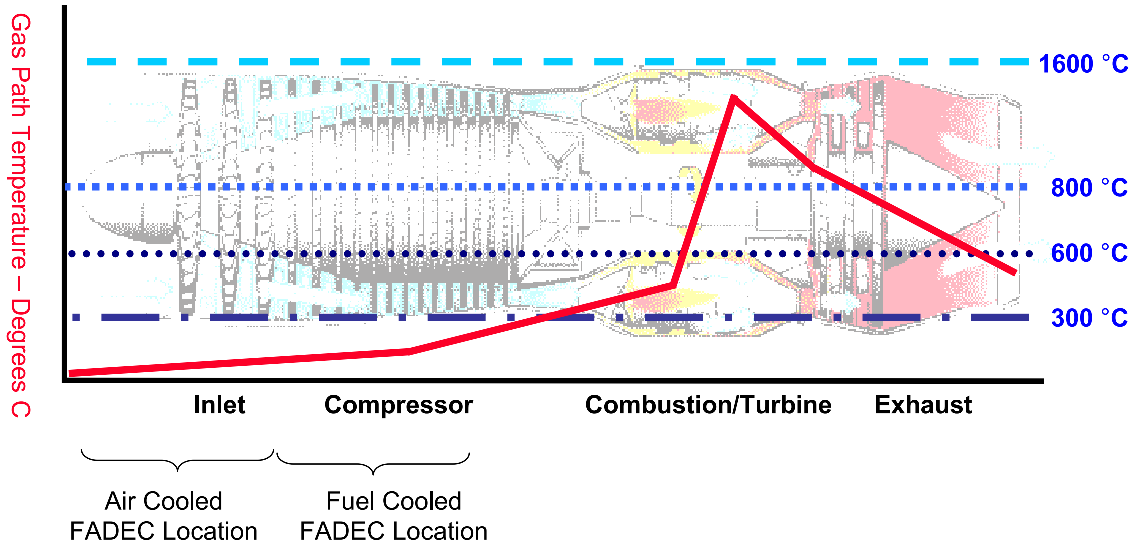


Figure 6: Temperature Profile of Typical Turbine Engine

Additional Advantages. Fault detection and isolation is improved. For example, when a thermocouple is malfunctioning, the problem could be in the thermocouple itself, in the cable connection to the FADEC control, or in the interface itself. The current maintenance procedure is to replace everything at once. If the thermocouple interface is distributed, then the faulty module can be replaced without replacing any other components in the process.

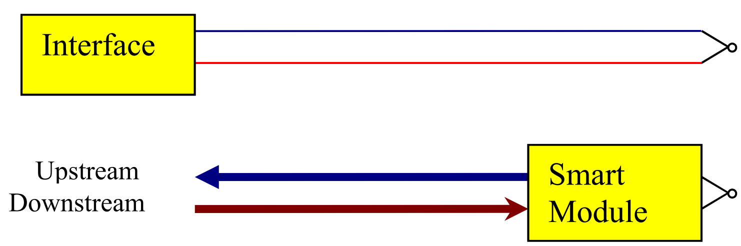


Figure 7: Sensors versus "smart sensors"

This Modularity provides for easy replacement of defects when they are found. This Modularity simplifies upgrades for new sensors, system reconfiguration, etc. as they are implemented.

The Smart System maintenance is streamlined (cost reduced) by enabling prognostic health management (i.e. predicting useful end-of-life)

Smart Node attributes. The Smart Node must have the following minimum attributes:

It must have an **extended temperature operating range**. (SOI electronics can operate up to 225°C.) It must be rugged enough to survive in the hostile engine environment.

It must be **low cost**. Even though high temperature components are more expensive, the smart node cannot exceed reasonable cost targets. Cost tradeoffs must be considered. By incorporating prognostic health in distributed nodes, millions of dollars can be saved in maintenance. Not only can the distributed nodes be serviced by less technical personnel, but also, expensive dismantling of engines and shipping to regional engine services centers for overhaul can be minimized.

It must have a **communication protocol interface**. The digital bus must be rugged, reliable, fault tolerant, and high enough in bandwidth to accommodate the interfaces of several effectors. In Figure 8 a preliminary estimate is made for an asynchronous protocol with the given characteristics.

It must have **enough intelligence** to meet the needs of the system. How much is enough? Every smart node needs **A/D conversion**. Some would like to off load Controller computations by having the smart node perform digital signal processing (**DSP) functions** – such as converting the analog voltage to a temperature (or pressure, or position etc.). Any electronic interface must have **fault detection and isolation** built in. And some smart nodes could provide **useful end-of-life estimations** for maintenance cost reductions.

Traffic Approximations – Necessary Bandwidth

- Multi-Drop Should be Supported to Allow Cable Reduction
- Indicates a 1MHz Bus is Required for an 8 DCM per Multi-Drop Bus
- Bus Speed Can Increased By Designer for Greater Bandwidth

Assume two command/response per DCM	
2	messages per DCM per minor frame
18	bytes send per message
18	bytes receive per message
250	microsecond lag between cmd/resp
1	Mhz Bus Freq
1	us per bit
1076	microseconds per DCM
8	# of DCMs in the multi-drop
8.608	milliseconds of comm time
10-17	milliseconds minor frame in typical Commercial minor frame

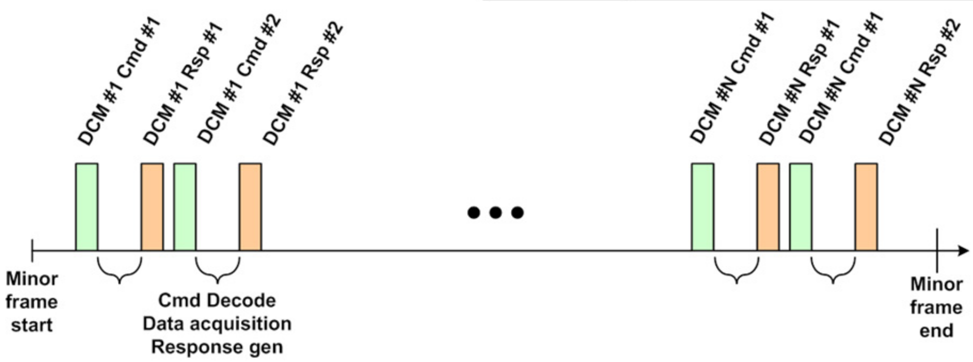


Figure 8: **Number of Nodes per Network**

II. Smart Nodes

Figure 8 shows a block diagram of a smart node.

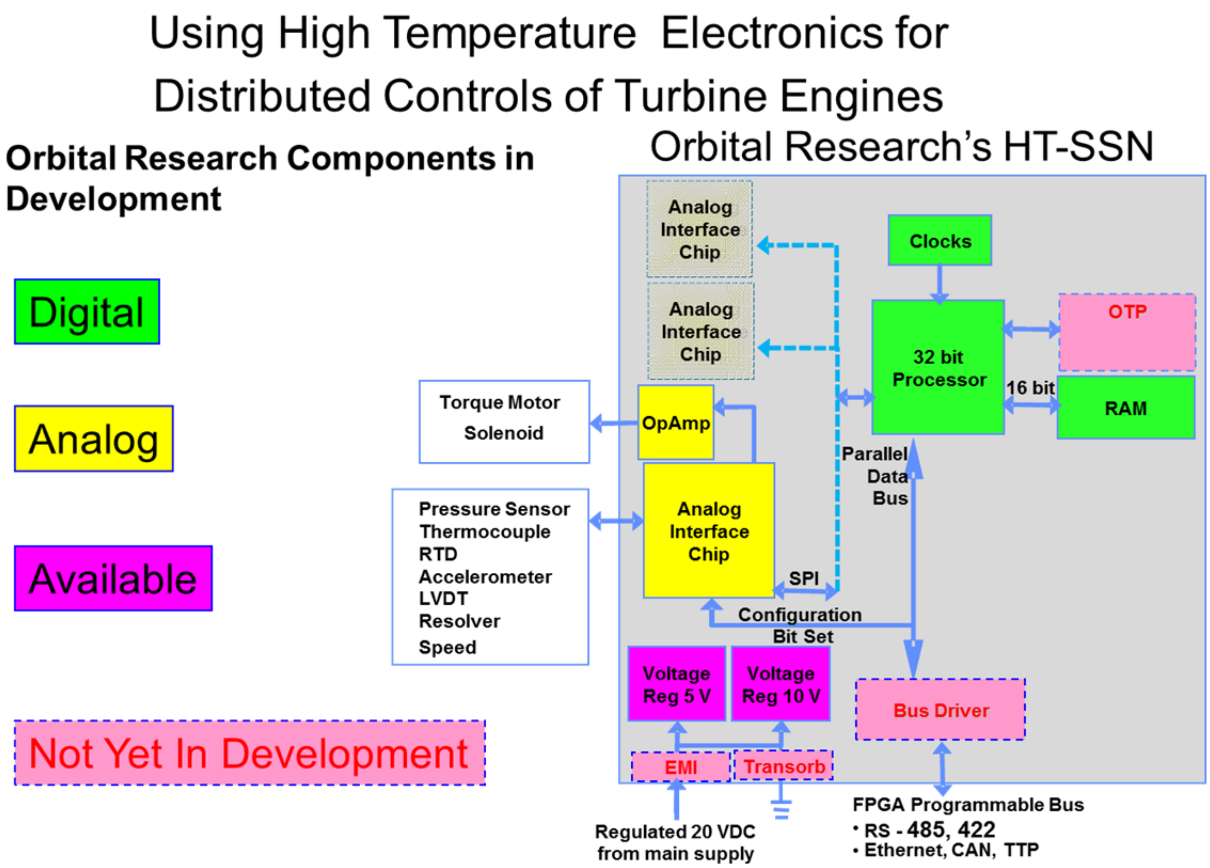


Figure 9: Smart Sensing Node

The main sections are analog (interface to sensors and drivers for actuators), digital (DSP, Communication, Diagnostics, Prognostics, sensor calibration, etc.), power regulation, and noise suppression.

III. Standardization

Since high temperature electronics are custom designed and fabricated ASICs, it becomes imperative that smart node standards be instituted and widely accepted in order to keep development and per piece costs to a minimum. This includes not only minimum hardware features, but also such things as protocol standards, operating temperature conditions and other

hostile environment survivability requirements. To date, there are two IEEE standards that apply to smart nodes. They are:

IEEE 1451.0 "Standard for Smart Transducer for sensors and Actuators – Common Functions, Communication Protocols, and Transducer Electronic Data Sheet (TEDS) Format."
IEEE 1451.3 "Standard for a Smart Transducer Interface for Sensors and Actuators – Digital Communication and TEDS Formats for Distributed Multidrop Systems.
DECWG_Node_Level_Req_Spec_Final-HoneywellProprietary.doc

In order to keep costs down it is imperative that the high temperature hardware be as generic as possible. What that means is that there should be one set of electronic components designed to interface to or be programmed for a wide variety of sensors and actuator interfaces.

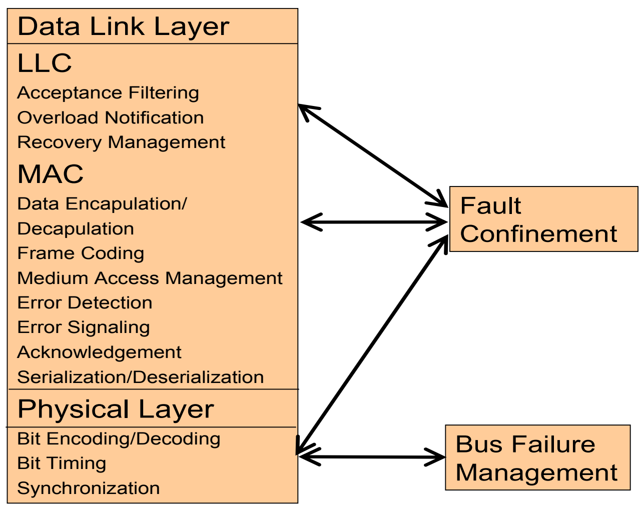


Figure 10: Protocol Layers Involved In Fault Detection

IV. Fault Tolerance

Fault Detection can be localized at a given smart node. Data bus fault detection, however is a more complicated process. Figure 8 shows a system level approach to fault detection on a digital data bus.

Redundancy (Alternate paths) should be built into the design of the network. Each system needs a fail-safe backup. **Figure 11** shows how this redundancy could be implemented in a communication bus environment.

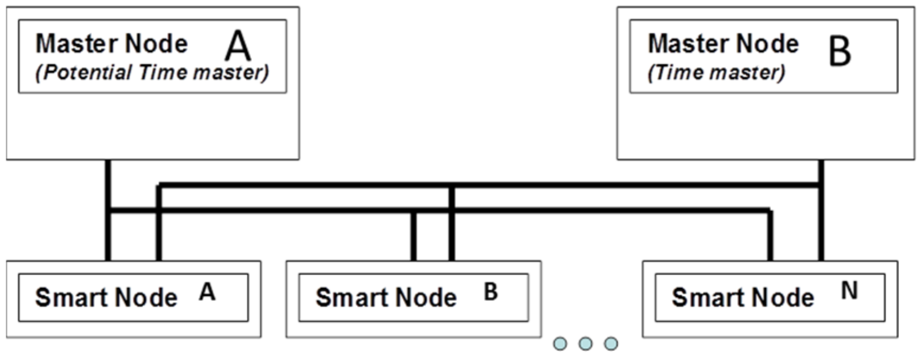


Figure 11: Multi-Smart Nodes Redundancy Management

The system should be **fail-safe**, to some extent. Digital bus drivers require a monitor of their output to disconnect when fault conditions are detected. No Smart Node can seize the communication line or flood the channel with spurious signals.

V. Prognostics

Prognostics is the reporting of sensors or actuators that are nearing the end of their useful life. The purpose of Prognostic Health Management is to repair systems before they fail, while maximizing useful life consumption, and to have the necessary parts, tools and maintainers waiting nearby to resolve the correct problem as quickly and efficiently as possible. This is estimated from a combination of tabulated usage hours, increased frequency of erroneous readings, or faulty actuation, and *a priori* knowledge of the possible failure modes of a given node.

Memory Storage Requirement. Depending on the type of mechanism, and the bandwidth of the data being monitored for its health, a significant amount of data storage may be required.

VI. Integration of Intelligent Sensor Network

Figure 12 shows a hierarchical system network of an aircraft turbine engine. The Distributed Intelligent Nodes provide real time sensor and actuator data to supervisory programs that can perform the required functions in a stable and reliable manner.

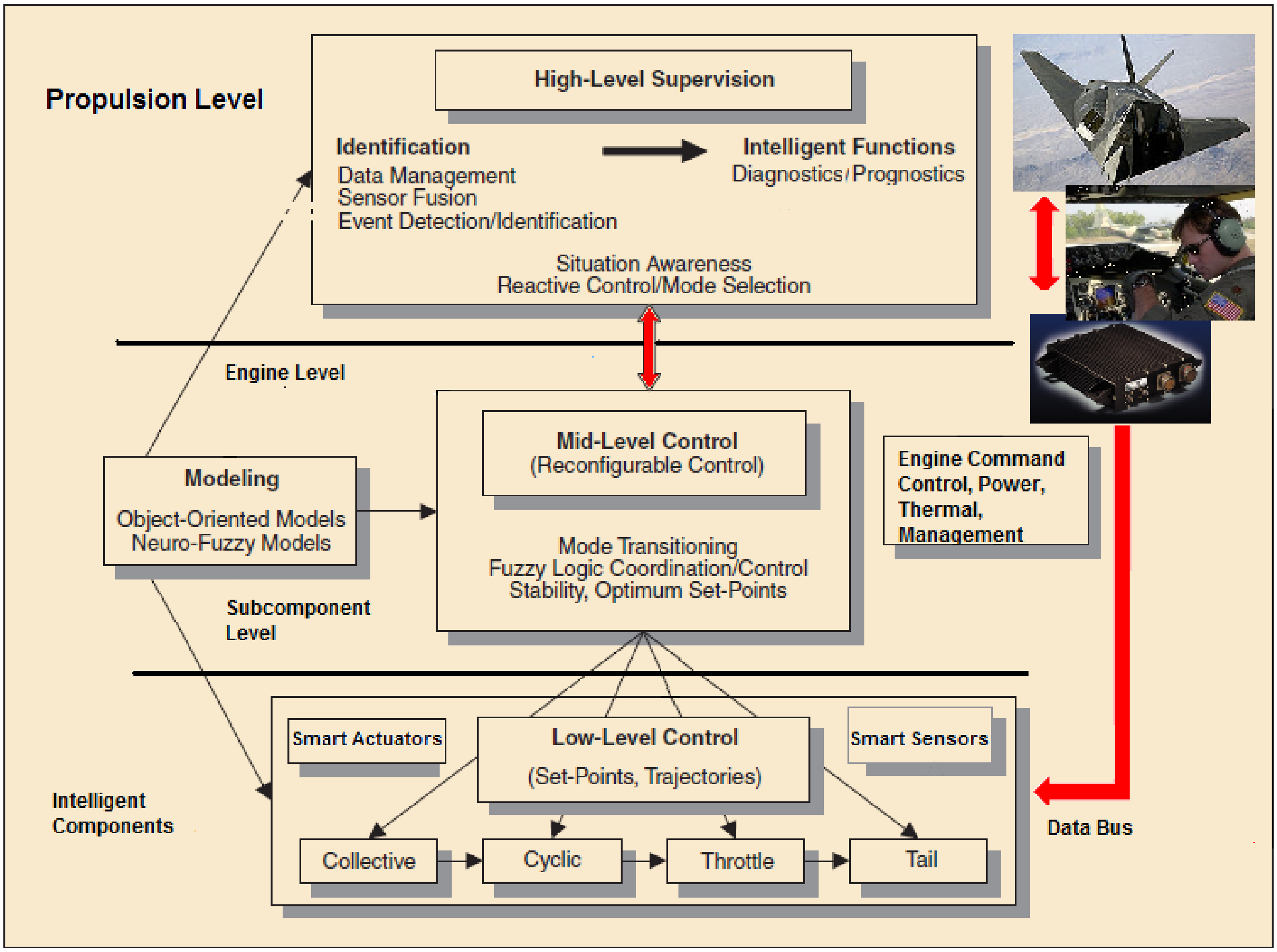


Figure 12: **Hierarchical Reconfigurable Distributed Control Architecture**

VII. Implementation

Implementation of Smart Nodes for Distributed Control has some challenges to overcome. High temperature electronics must be created that are generic, rugged, cost effective and reliable. Each high temperature component is designed as an application specific integrated circuit (ASIC). The application specific to any given IC must be adaptable to a large number of design requirements, because the development costs of any ASIC is large, and the cost of components can be reduced only by increasing volumes.

The next challenge is therefore to collaborate with manufacturers to standardize the specific components needed for each of their distributed control system designs. This effort is being addressed by a consortium of manufacturers, military and government agencies

And finally, the components themselves must be qualified, verified, and second-sourced in order to be placed on any manufacturers' Approved Vendor List. No component can go on any engine unless it is listed on a manufacturers' AVL.

Conclusion

Control of turbine engine systems can be greatly enhanced by incorporating distributed control of sensors and actuators. The necessary parts to enable introduction of this type of system architecture are ruggedized high temperature ASICs. By careful and prudent design, these ASICs can be standardized and generic to allow application to a wide variety of control structures. The advantages of distributed processing have been shown to be increased noise immunity; ease of sensor calibration; fault tolerance and fault detection, isolation, and recovery; as well as prognostic capabilities.

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Intelligent Turbine Engine Controls

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Alireza R. Behbahani, Ph.D.

Orbital Research and Air Force Research Laboratory

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Abstract

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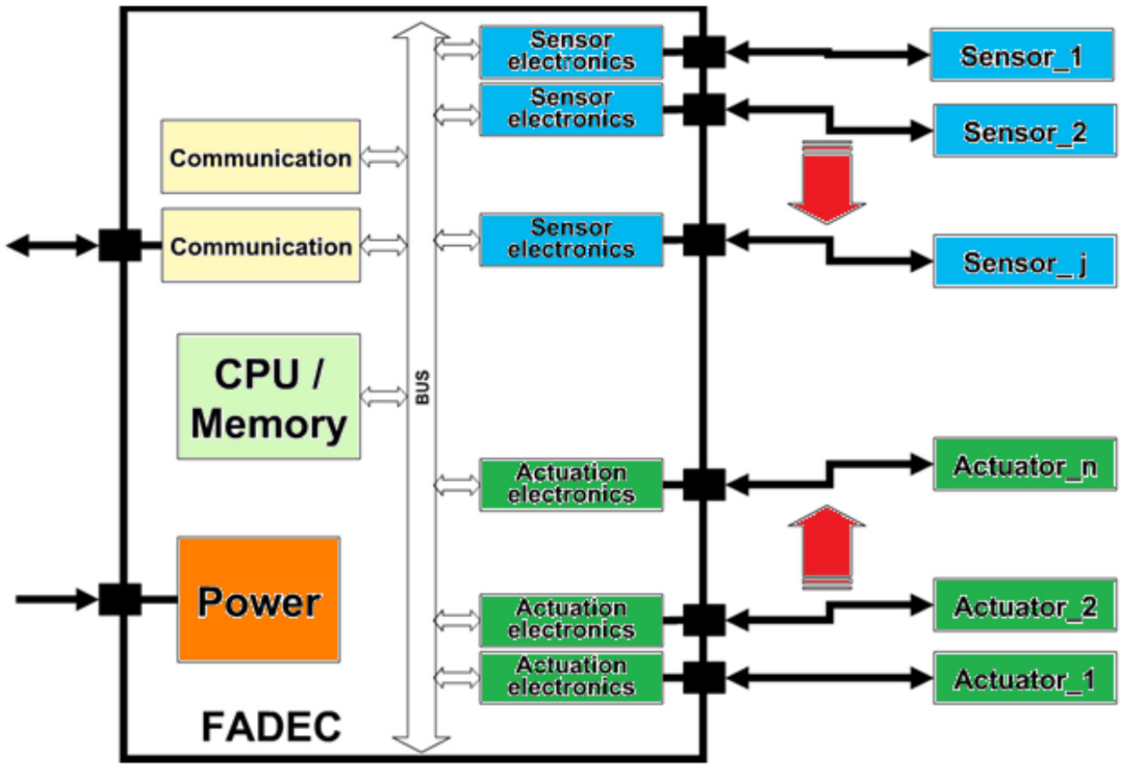
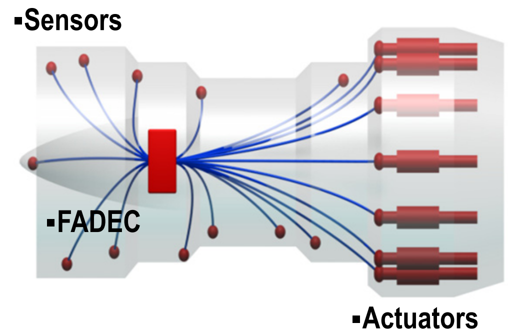
Presenter
Mike Willett

- Project Engineer: Micro Devices
- Last 8 years spent in developing high temperature ICs and Control Modules
- Experience in COB and Flip Chip miniaturization
- 30 year career in circuit design and pcb layout

Centralized Control System





Each function resides within the FADEC and uses unique Point-to-Point analog connections to System Effectors

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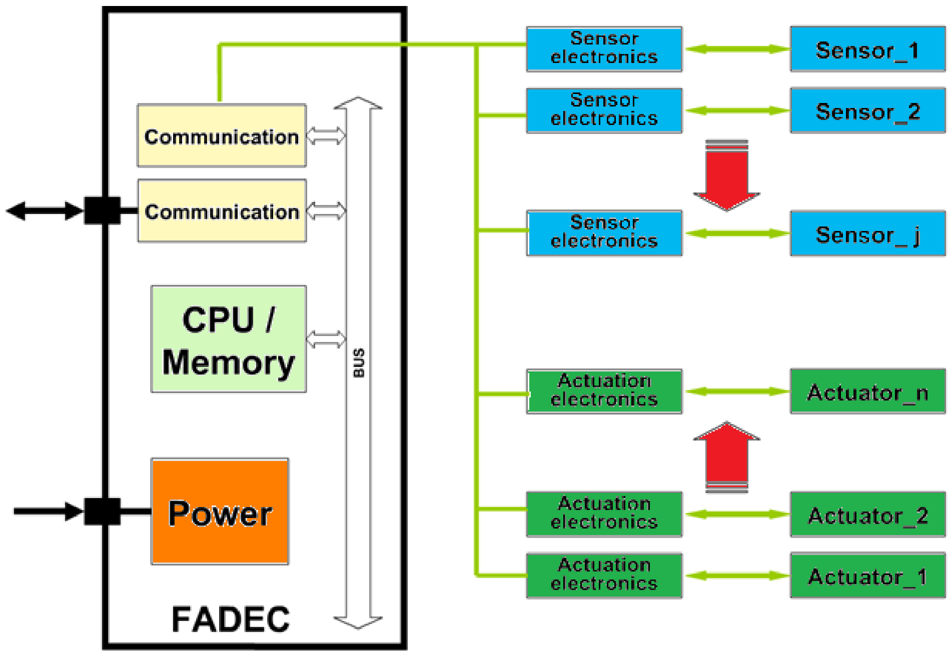
Distributed Control System



Functions are distributed outside the FADEC and are communicated via a common Interface Standard

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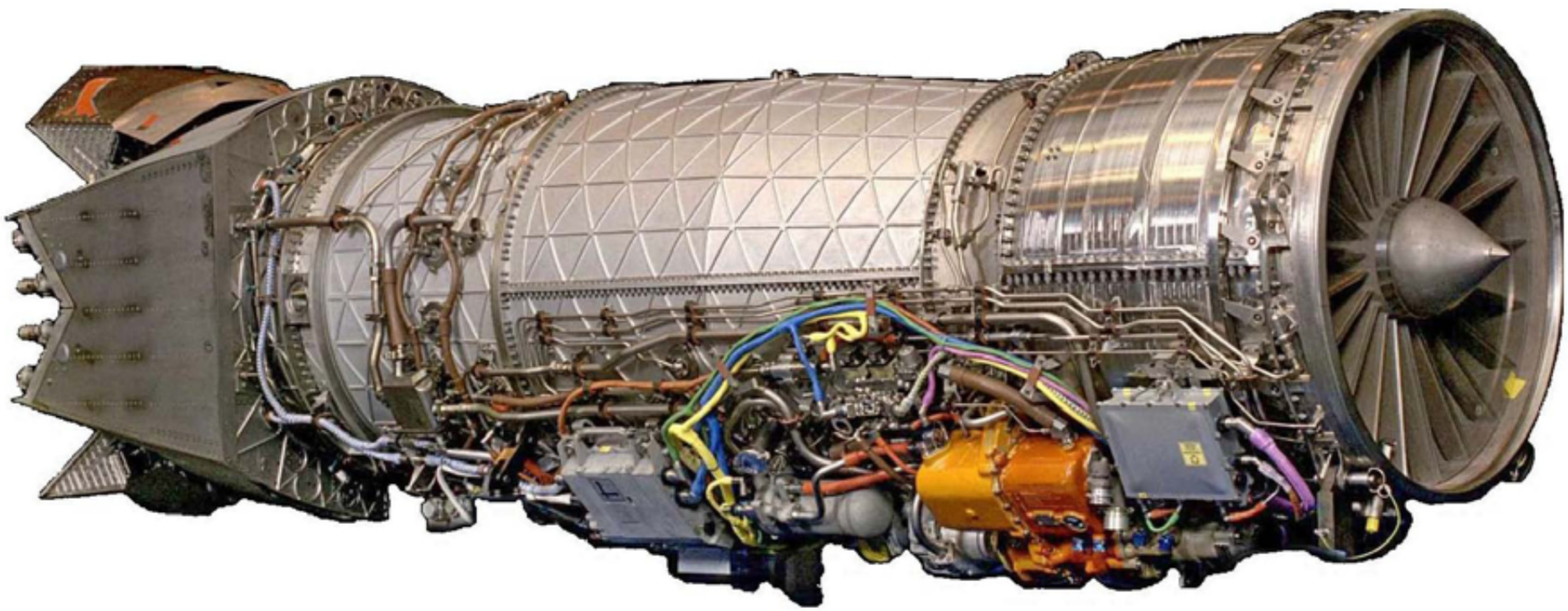
Turbine Engine Showing Controls



Engine Controls and Accessories Comprise a Substantial Portion of Total Engine Weight as Shown in This Core-Mounted Fuel-Cooled Military Control Implementation
(Courtesy of Pratt & Whitney)

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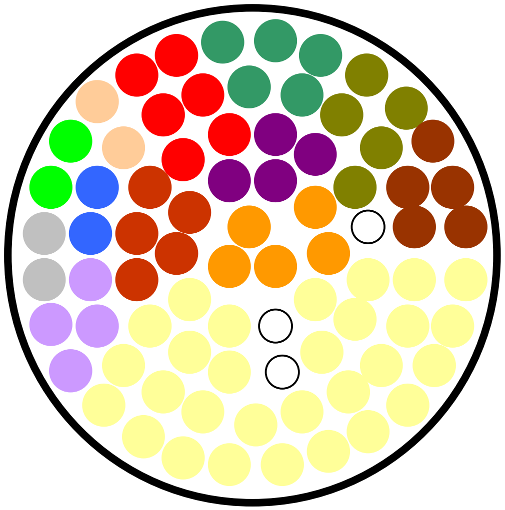
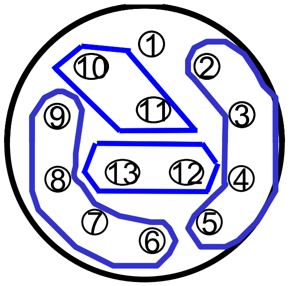
Cable Bundle from Typical FADEC and Replacement



79 pin (20 Devices)



13 pin (Redundant Comm)

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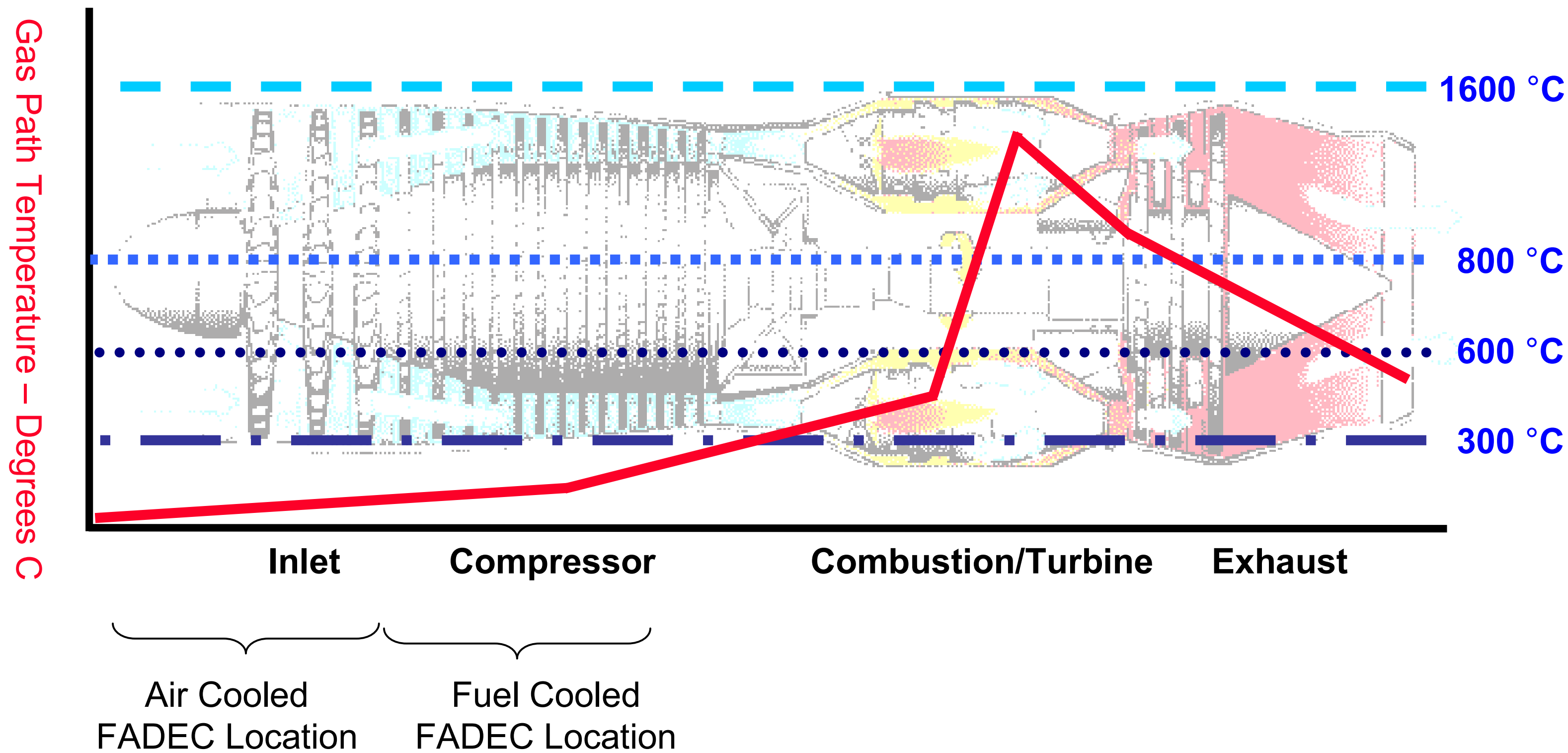
Temperature Profile of Typical Turbine Engine



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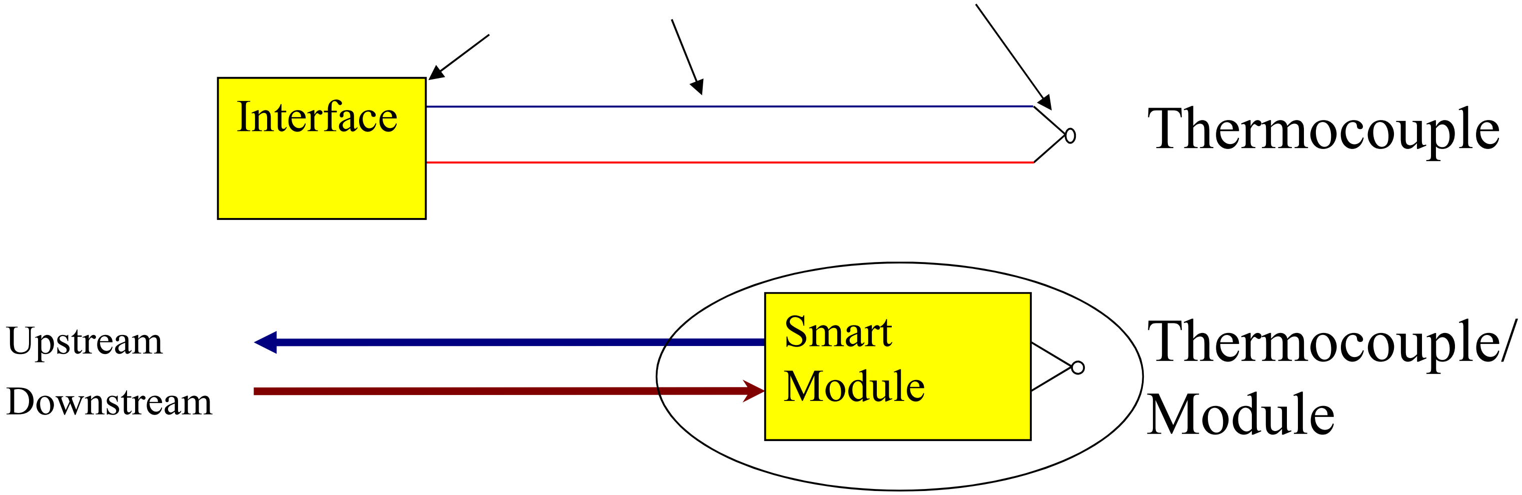
Modularity for Streamlined Maintenance

Where is the failure located?

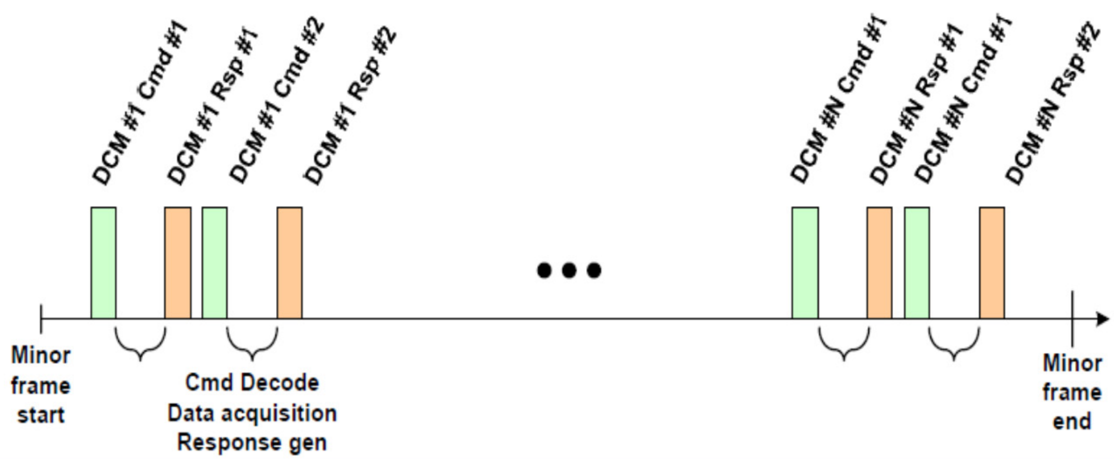


What Happens When a Thermocouple Fails?

Traffic Approximations – Necessary Bandwidth

BAE SYSTEMS

Assume two command/response per DCM	
2	messages per DCM per minor frame
18	bytes sent per message
18	bytes received per message
250	μs lag between cmd/resp
1	Mhz Bus Freq
1	μs per bit
1076	μs per DCM
8	# of DCMs in the multi-drop
8.608	ms of comm time
10-17	ms per typical minor frame



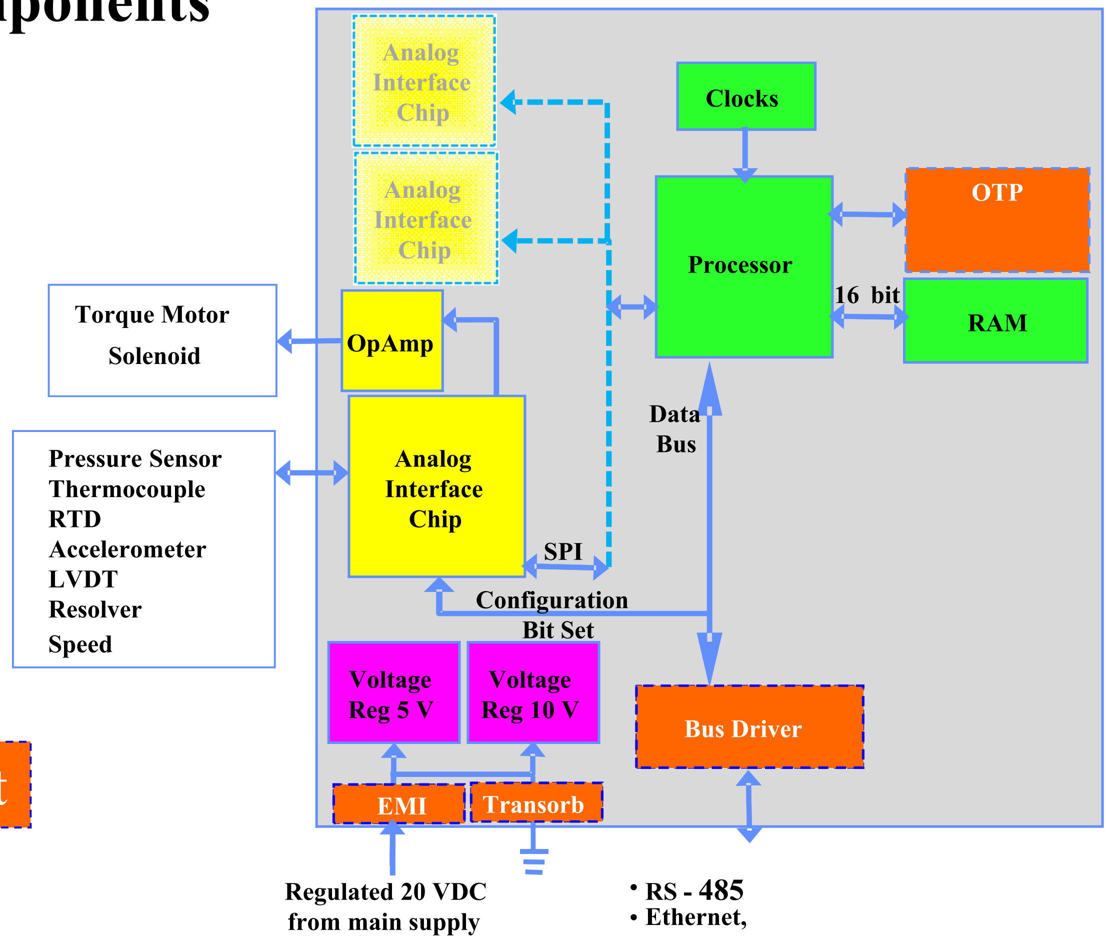
Orbital Research Components in Development

Digital

Analog

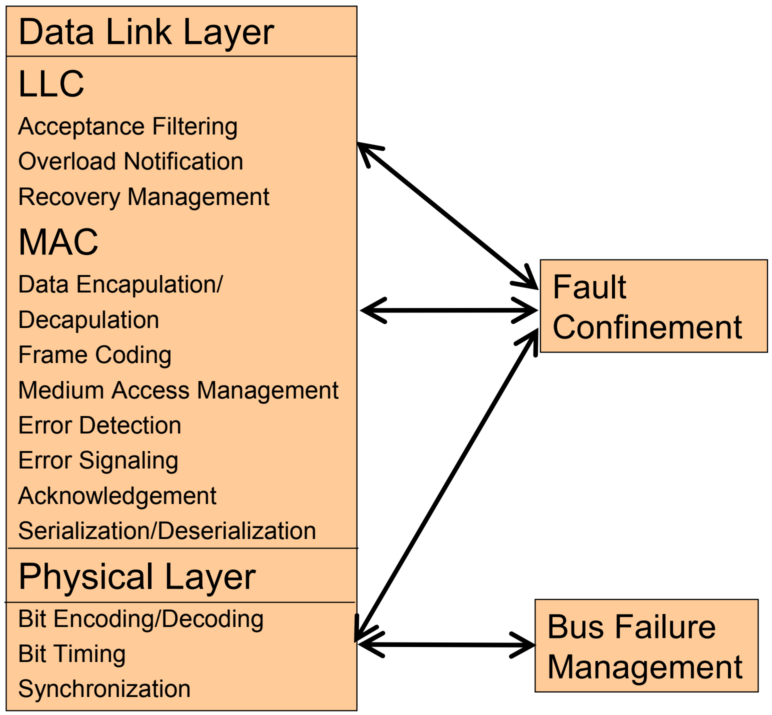
Available

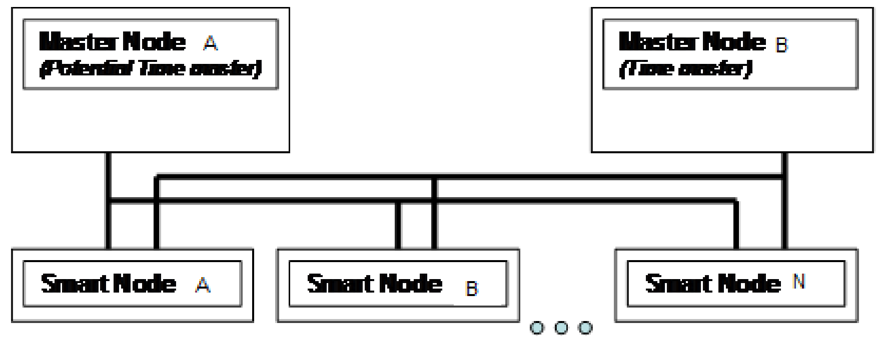
Now In Development



Orbital Research's HT-SSN

Fault Tolerance



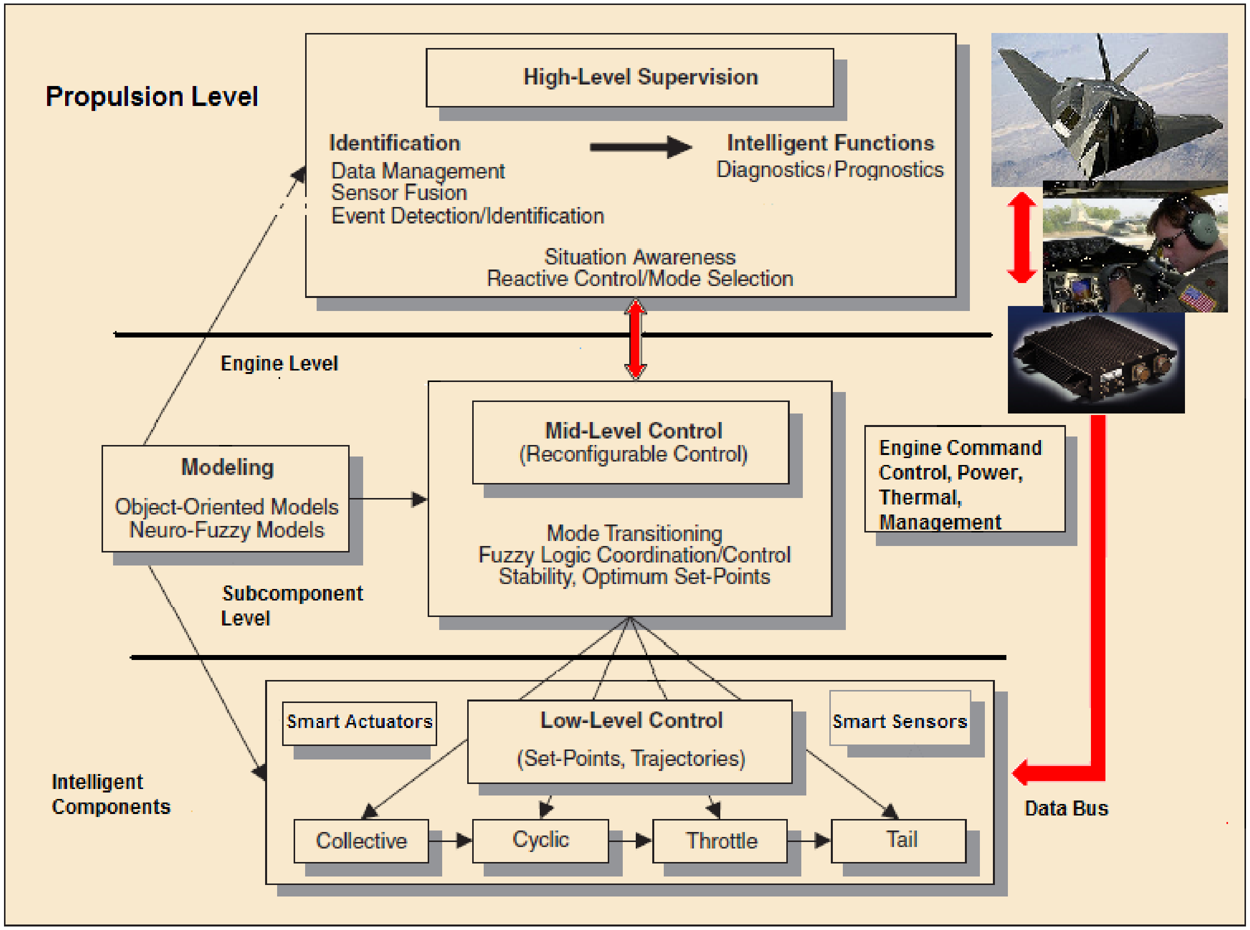


Multi-Smart Nodes Redundancy Management

Protocol Layers Involved

In Fault Detection

Integration of Intelligent Sensor Network



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Implementation

- Challenges to Overcome
  - Generic
  - Rugged
  - Cost Effective
  - Reliable
- Each High Temperature Component is an ASIC
  - Development costs are high
  - Standards in the process of being defined by DECWG
  - Need Qualification and Verification
  - Each Component must have a 2nd Source

Conclusion

- Distributed Control provides added benefits
  - Increase Noise Immunity
  - Sensor Calibration Made Easy
  - Fault Detection and Isolation
  - Fault Tolerance
  - Prognostic Functions Can be Implemented
  - Weight Reduction
- Requires ruggedized high temperature ASICs
  - Standardized
  - Generic
  - 2^{nd} Sourced